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# Historical overview of John M. Norman's involvement in the development of several key instruments for biophysical measurement

J.M. Welles[a], M.C. Anderson[b,*]

[a] LI-COR Biosciences, Inc., Lincoln, NE, United States
[b] USDA-ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD, United States

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ABSTRACT

If you have ever used a quantum sensor, or measured the LAI of a plant canopy, or lugged around a portable photosynthesis system, then you are likely the beneficiary of just some of John Norman's work in instrumentation. In his nearly 40-year career of trying to understand plants and their environment through modeling and measurements, John's boundless creativity and enthusiasm have never let lack of available instrumentation stop him for long. He leaves behind an impressive wake of gadgets and devices. Most served their purpose, and provided the missing information being sought. Some of his devices have gone on to world-wide success, while others are found only in the dust of former students' memories. John's legacy, however, is clear, and goes well beyond instrumentation: he is a joyful, creative resource, as all who have had the privilege of knowing him can attest.

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## 1. Introduction

Professor John Norman has had a long and fruitful history of instrumentation development. A list of the devices he has contributed to include:

- Quantum sensor (Norman et al., 1969)
- Various traversing devices for measuring sunflecks in canopies (Miller and Norman, 1971; Perry et al., 1988; Norman and Jarvis, 1974)
- Drag anemometer for turbulence measurements (Norman et al., 1976; Perry et al., 1978)
- An aerosol sampler (Pena et al., 1977)
- A real time computer graphics system for forecasting (Cahir et al., 1981)
- Microlysimeter for measuring ET and drainage (Cook and Norman, 1982)
- Root length measuring device (Wilhelm et al., 1983)
- DEMON, the CSIRO Leaf Area Index instrument (Lang et al., 1985.)
- A portable $CO_2$ calibration device (LI-COR literature)
- A jig for measuring bidirectional reflectance from leaves (Norman et al., 1985)
- The "Pine Cone" sensor, a device for measuring the angular distribution of diffuse radiation above and within canopies (Hutchison et al., 1986)
- Lighted bar or light-pipe used at night in turf (Kopeck et al., 1987)
- A field portable photosynthesis system (McDermitt et al., 1989)
- LAI-2000 Leaf Area Index instrument (Welles and Norman, 1991)
- Soil respiration chamber (Norman et al., 1992)
- A device for measuring directional emissivity (Norman et al., 1994)
- A device for measuring the water holding capacity in pork (Kim et al., 1995)
- Heated needle anemometer (Bland et al., 1995)
- Multiband vegetation imager (Kucharik et al., 1997)
- Equilibrium tension lysimeter (Brye et al., 1998)
- A high precision infra-red radiometer (Baker and Norman, 1999)
- A soil and topography mapper (Zhu et al., 2004)
- A device for measuring field-scale runoff (Bonilla et al., 2006)

This paper looks at some of these devices from the early part of John's career, and shares the story of how they came about.

## 2. Early career

John Norman received a Bachelors degree in Physics and an M.S. in Soil Physics at University of Minnesota. In 1967, he started on his PhD at the University of Wisconsin, working under Dr. Champ Tanner on light distribution and canopy architecture in plant canopies. One of John's first efforts was to develop a silicon cell PAR sensor (Norman et al., 1969). This was later improved by LI-COR and marketed as the LI-190 quantum sensor. In analyzing light measurements made under a corn canopy, John recognized that there was significantly more radiation under the canopy than the

* Corresponding author. Tel.: +1 301 504 6616; fax: +1 301 504 8931.
*E-mail address:* martha.anderson@ars.usda.gov (M.C. Anderson).

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conventional gap-fraction approach could explain. With Dr. Ed Miller from the Physics Department, it was determined that light from the penumbra of the sun was not being accounted for in the standard theory (Miller and Norman, 1971; Norman et al., 1971).

John received his PhD in March 1971 and embarked on a post-doctoral position in the Botany Department at the University of Aberdeen under Dr. Paul Jarvis, addressing the effects of clumped canopy architecture in Sitka spruce (Norman and Jarvis, 1974, 1975). In 1972, John was offered a position at Penn State to work on canopy–atmosphere interactions, joining a group of micrometeorologists including Dr. Dennis Thomson and Dr. Hans Panofsky. John took on a wide range of projects at Penn State, from developing a drag anemometer for measuring in- and above-canopy turbulence, to modeling the effects of orchard heaters used for frost protection (Fig. 1). It was at this time that John also began work on a career-long endeavor, development of the soil–plant–atmosphere Cupid model (Norman, 1979; Norman and Campbell, 1983; Norman and Arkebauer, 1991), which would come to embody the insights accumulated from his own and others' work in this continuum.

## 3. Carbon exchange

### 3.1. Porometry

In 1978, John took a faculty position in the Agronomy Department at the University of Nebraska – Lincoln. Lincoln was also the home of a small company named LI-COR. John visited them during his interview trip, and met the owner Bill Biggs who shared John's interest in quantum sensors. LI-COR also had made a series of porometers over the years (LI-60, LI-65), and was working on an instrument that became the LI-1600 steady state porometer. John was interested in porometers and the insight they provide about stomatal functioning, and had purchased a Delta T Mark II porometer with some of his start-up money. Soon, John was working with LI-COR to do a formal comparison of all of these porometers (Fig. 2).

The results of the comparison (Fig. 3) showed good agreement between the LI-1600 and the Delta T, but also clearly showed that the LI-65 had problems. As a result, LI-COR discontinued its production. Interestingly, this move met with customer resistance, since many liked the low price, and did not mind the uncertain results.

### 3.2. Portable photosynthesis instrumentation

At about this time, researchers (e.g. Farquhar et al., 1980) began to demonstrate the role that leaf photosynthesis plays in stomatal behavior, and it became clear to John that simple porometer measurements would never be sufficient to fully understand stomatal function. The sorghum physiology group at the University of Nebraska had been using a field technique involving large chambers and syringes to estimate carbon uptake in the field (Clegg et al., 1978). The plant part to be measured was enclosed in a

**Fig. 1.** John Norman, circa 1977, getting photographic documentation of canopy structure in an orchard.

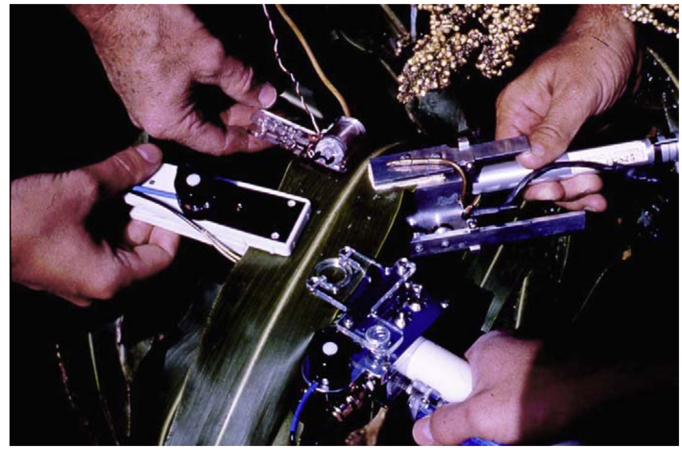

**Fig. 2.** Porometer comparison conducted by John Norman. Shown are the LI-COR LI-65 (upper left), Delta T Mark II (lower left), a Kaufman convective chamber porometer (upper right), and the LI-COR LI-1600 steady state porometer (lower right).

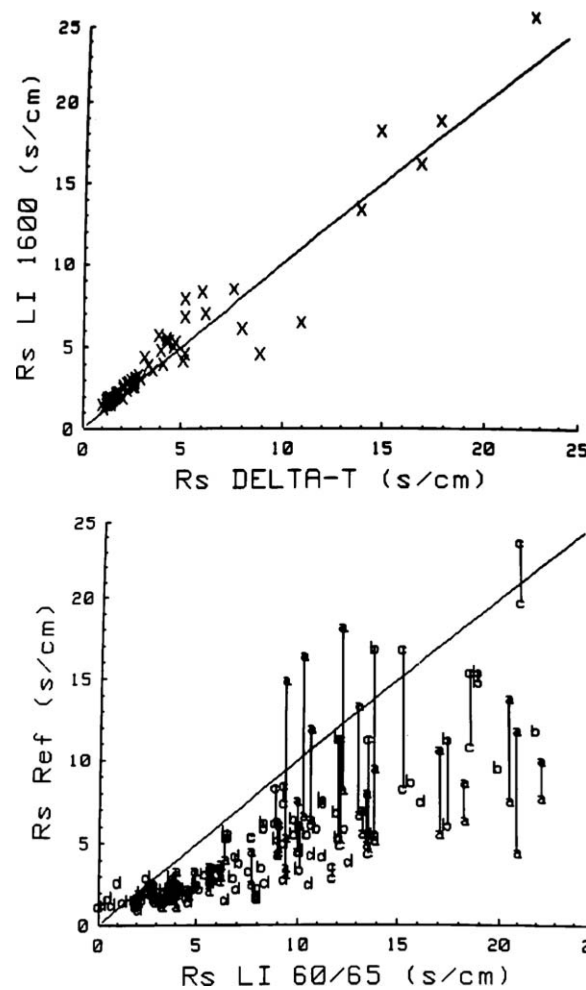


**Fig. 3.** (Top) Comparison between the Delta T and LI-1600 porometers. (Bottom) The LI-65 had problems, and LI-COR discontinued production.

**Fig. 4.** John Norman (right) making "simultaneous" measurements of stomatal conductance and photosynthesis, using a Delta T porometer, and a home-made chamber with syringes.

clear plastic chamber, and two syringes of air were extracted a fixed time apart. The air in the syringes was measured later by injecting them into a $CO_2$ analyzer back in the lab. John adapted this technique by adding mixing fans to the chamber to minimize boundary layer resistance, and by making porometer measurements before and after the $CO_2$ measurement (Fig. 4).

The next innovation involved placing the sensor head of the LI-1600 porometer into the leaf chamber so that stomatal conductance could be measured during the period when the syringes were extracted (Fig. 5). This was no longer a steady state conductance measurement, but a closed-system transient, whereby the conductance is computed from the rate of change of water vapor with time.

A major breakthrough came when John came across a company named Liston-Edwards in Newport Beach, California, that made a $CO_2$ gas analyzer that was small enough to be portable, required low enough power to be run by a battery, and had specifications suitable for leaf photosynthesis measurements. John obtained a sample, and went to work adapting it for his purposes. The result was a John Norman classic: a portable field photosynthesis system in five 'easily'-worn pieces (Fig. 6).

Making a practical photosynthesis instrument would require help, so John tried to interest LI-COR in taking this system on as a product. Bill Biggs was initially reluctant for two reasons: (1) it was a transient system, and after the difficulties with the transient LI-65, Bill was definitely in the steady state camp; and (2) it would be expensive, and the market size was unknown, since nothing like John's five piece system had ever been commercialized before. Eventually, LI-COR took on the project, and in the first prototype, the unit consisted of three pieces, two worn around the waist, with the gas analyzer optical bench inside of a very large chamber handle (Fig. 7).

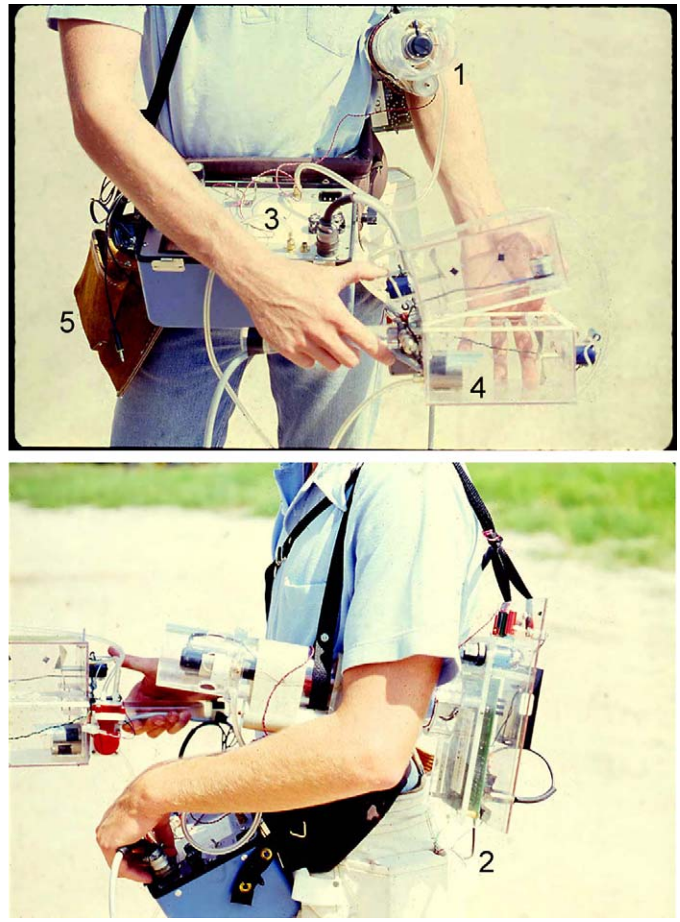


**Fig. 6.** A field portable photosynthesis system in five pieces: (1) Liston-Edwards gas analyzer optical bench and board; (2) the analyzer power supply; (3) LI-1600 console; (4) leaf chamber; (5) tape recorder for data logging.

The final configuration moved the entire IRGA to its own box beneath the control console, and the LI-6000 Portable Photosynthesis System was born. Best of all, there was no more tape recorder; the console did all the calculations on the spot, so for the first time, it was possible to see simultaneous conductance and photosynthetic values right in the field.

Being a good student of Champ Tanner, John understood the importance of sensor calibration, and this included his photosynthesis system. This involved calibrating the $CO_2$ analyzer, a two-step process: zeroing (making it read zero with no $CO_2$ present), and spanning (making it read a known concentration correctly). Zeroing in the field was not hard, as $CO_2$-free air could be obtained with a chemical scrub tube. Setting the span was another issue, as taking a tank of compressed gas to the field is usually problematic. John came up with a device that could solve the problem, by mixing pure $CO_2$ as measured in a microliter syringe with a liter of $CO_2$-free air. Fig. 8 shows his original sketch.

The LI-6000 started LI-COR down the path of portable photosynthesis systems, and was followed by the LI-6200 with a LI-COR-built gas analyzer, and then the LI-6400, which is a steady state system with the gas analyzers built into the leaf chamber.

**Fig. 5.** LI-1600 steady state porometer modified to measure humidity in a leaf chamber equipped with $CO_2$ syringes, barely visible on the right.

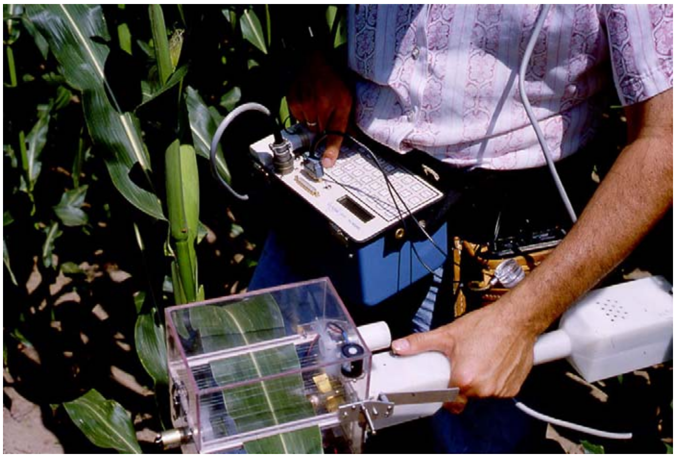

**Fig. 7.** The first prototype of LI-COR's implementation of John's photosynthesis system had the IRGA in the handle.

## 4. Canopy structure

John's dissertation and post-doctoral work was heavily involved with radiation transfer through plant canopies. This topic formed an integral part of his modeling work, providing the framework on which to add physiological responses and atmospheric processes. Forward modeling – predicting light penetration given the canopy properties – was relatively straight-forward. There was, however, the intriguing notion of inverting the model; that is, to make some radiation measurements from which the canopy properties could be computed. But, what model to invert, and what parameters to measure?

### 4.1. Model trains

One approach was to measure sunflecks, the fraction of area under a canopy that is sunlit. Measuring this value at several sun angles produces a series of equations with nearly as many equations as unknowns, yielding hope for a numerical solution. John began exploring this approach while at Penn State and continued at Nebraska. We (the lead author was a student of John's at Penn State and Nebraska) built a traversing system using HO

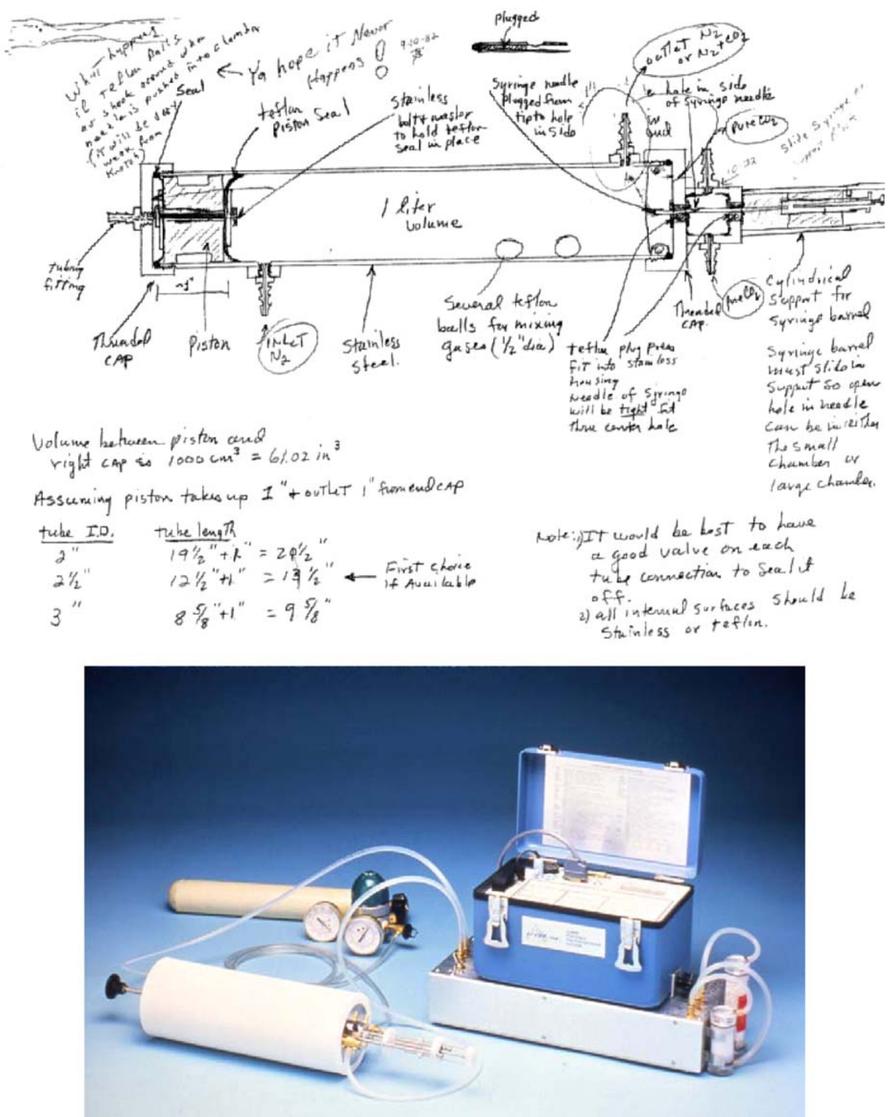


**Fig. 8.** John's original sketch of his mixing cylinder for calibrating the IRGA, along with the final embodiment of the cylinder with the LI-6000 Photosynthesis System.

**Fig. 9.** Sunflecks measured with a model train. The locomotive had to be "streamlined" a bit to prevent snagging foliage.

scale model railroad equipment (Fig. 9). The track lay in 30 feet of aluminum U-channel. One of the cars on the train contained a light sensor and two circuits: one accumulated charge all the time, the other only when the signal from the sensor was above some threshold value. Pulling the train was a model of a Heisler geared logging locomotive. The measurement consisted of sending the train down and back, measuring the charge on the two circuits, and ratioing them to yield sunfleck fraction for that sun angle. This would be repeated over the course of a half-day to cover a range of sun angles. Why a model train? In retrospect, we think it was largely a scheme on John's part to get one of his model railroad fanatical students out of the lab and into the field.

### 4.2. Pine Cone Sensor

Another approach was to look at how the distribution of diffuse radiation changes with angle as one gets deeper and deeper into a plant canopy. John knew from modeling that there is a pronounced effect, but the problem was how to measure this distribution of radiation. While at Penn State he hit upon an idea for a sensor that, given its shape, came to be known as the Pine Cone Sensor (Figs. 10 and 14). It consists of a stack of photodiodes in a diffusing column, with each segment of the column separated from the others by fins. Thus, each photodiode is exposed to a different angular ring of the sky above. He found a machine shop to take on the task before he left Penn State, and took delivery of the result in Nebraska.

**Fig. 10.** The Pine Cone Sensor shown with a Campbell Data Logger. When used in direct sun, it had a shadow band, shown on the right.

Inverting Pine Cone data consisted of running a forward model to predict diffuse distributions under a range of leaf area indices, then finding the one that came closest to matching the measured distribution.

### 4.3. DEMON

In 1983, John took a three-month leave to visit Canberra, Australia. He took along his Pine Cone Sensor, and his algorithms for inverting sunfleck data. While there he spent some time with Dick Lang, who was looking for one more project to work on before he retired. Dick got very interested in the inversion problem, and went to work studying what John had done so far. They came up with the idea for a simple, hand-held threshold detector, not unlike the one on the model train back in Nebraska. The canopies of interest in this case were large trees, not crops, so carrying the sensor was an option. A sighting device was added so the operator could keep the sensor aimed at the sun while walking. Eventually, this device became a commercial product, marketed under the name DEMON (Fig. 11). Dick Lang did a lot of pioneering work as part of his "final project". He unearthed an analytical solution to the sunfleck inversion problem that made the solution very simple (Lang, 1987). He figured out how to deal with gaps in the canopy, such as caused by rows, in a rigorous fashion (Lang and Xiang, 1986). He also deduced from Cauchy's Theorem that indirect techniques for determining canopy structure were in fact computing one half of the surface area of the foliage, instead of a projected area (Lang, 1991).

### 4.4. Searching for the LAI-2000

LI-COR was interested in developing some sort of canopy structure sensor. The model train approach did not seem viable,

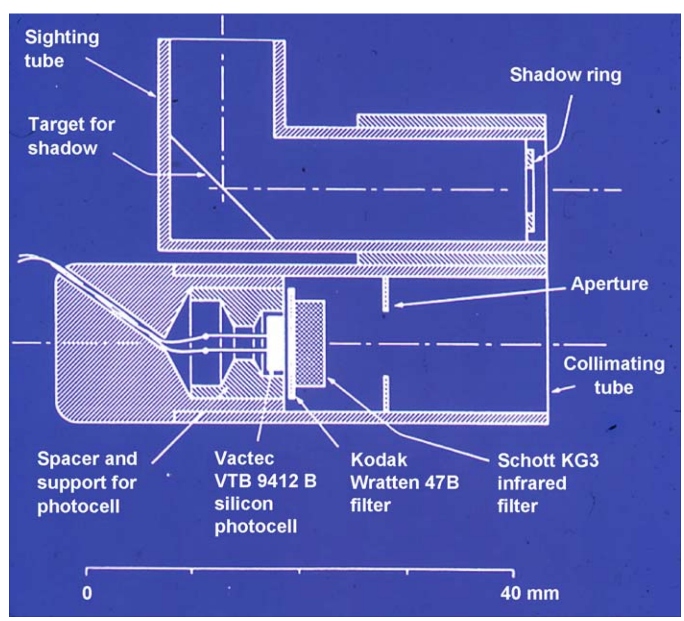


**Fig. 11.** A schematic of the DEMON sensor for measuring sunfleck fraction. The sun would be to the right.

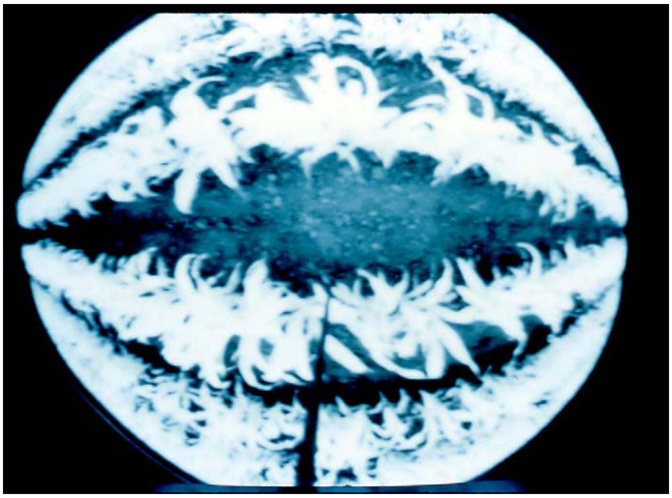

**Fig. 12.** A near IR hemispherical photo looking down at corn. The idea was to try a gap-fraction inversion based on the dark soil and bright leaves.

and was quickly ruled out. It was the mid-80s however, and the idea of using a digital camera with a fisheye lens to do canopy structure work started to seem a possibility, so John spent one summer month working with LI-COR investigating that approach. We put an IBM PC with a Frame-Grabber card in Bill Bigg's van, and attached it to a camera. Power came from a portable generator. We used visible and far-red filters, looked down on short canopies, up through taller canopies, and collected data in a variety of settings. Unfortunately, all data and photos from that experiment are long gone, save one fisheye near infra-red photo of a row of corn (Fig. 12). The conclusion from this work was that it was a viable method, but the technology was not there yet for an inexpensive field portable instrument. The Pine Cone Sensor also seemed a possible way to proceed, and was seriously considered.

Champ Tanner had meanwhile miniaturized the Pine Cone, and improved its angular response. All that was missing was a robust, practical, inversion algorithm, and we put a fair amount of effort into finding such a thing. Fig. 13 illustrates typical results when comparing inverted LAI with direct measurements in corn. Finally, and perhaps out of desperation, we tried treating the Pine Cone data as if they represented direct beam transmittance, and inverting it using a gap-fraction analysis. There was good reason to not try this sooner: much of the radiation seen by the sensor beneath the canopy is scattered, so simply ratioing above and below readings would significantly overestimate gap fractions. Surprisingly, applying the sunfleck analysis to the corn data yielded much less scatter in the comparison, and nearly followed the result predicted by the model.

Now the question became, how to optimize the Pine Cone Sensor for sunfleck measurements? Several ideas were considered until one day, a LI-COR engineer happened to notice a display of door peep-hole viewers while in a hardware store. This miniature lens idea led to the final embodiment of the LAI-2000 (Fig. 14). Whereas the Pine Cone Sensor used physical fins to partition its view into five angle classes, the LAI-2000 would accomplish the same thing optically, with a fisheye lens and a concentrically ringed detector. The approach had a further advantage of allowing the incoming radiation to be easily filtered to various wavelengths of interest. While the production units would ultimately use a low-pass blue filter to minimize effects of scattering in the canopy, we also experimented with a narrow band red filter (slightly darker foliage, but much darker sky) and a near infra-red filter (dark sky

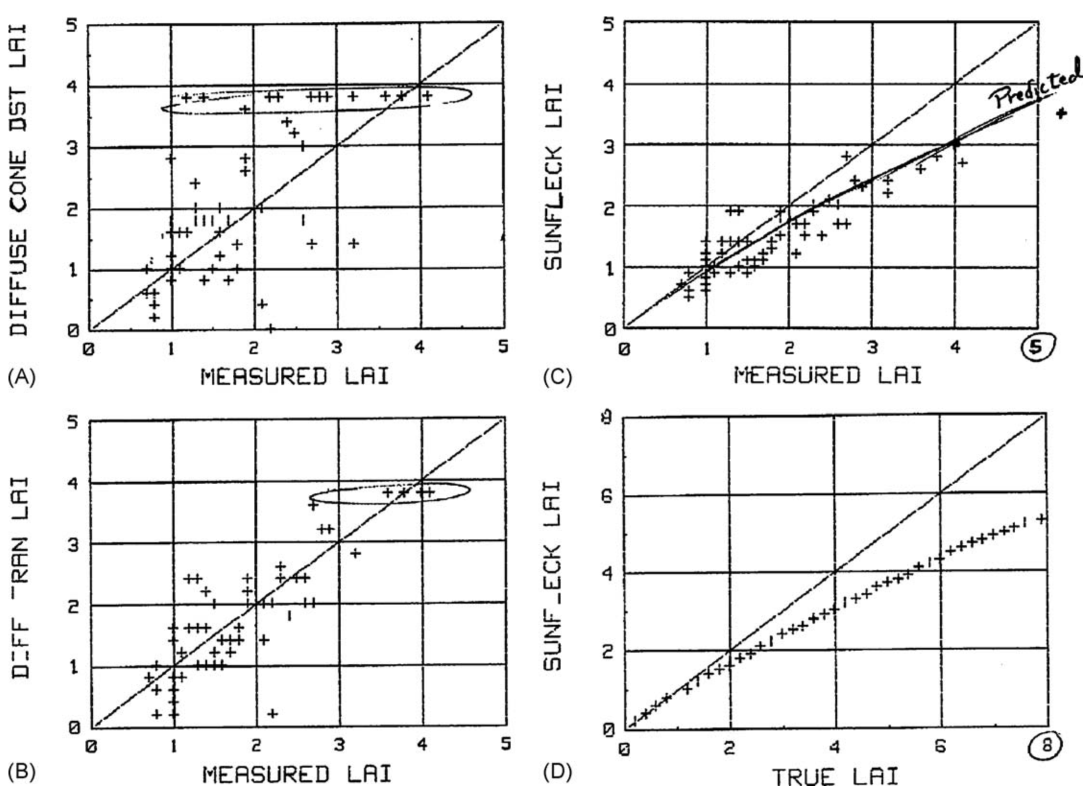


**Fig. 13.** Three of many attempts to relate Pine Cone Sensor output to Leaf Area Index. (A) LAI inverted from the measured diffuse distribution compared with directly measured LAI. The model did not consider LAI values greater than 3.8, hence the cluster of circled points. (B) LAI inverted from a simple integrated diffuse transmittance reduced the scatter somewhat. (C) LAI inverted from a gap-fraction treatment of the data has the lowest scatter. The hand drawn curve labeled "Predicted" comes from (D), a theoretical treatment for how the Pine Cone Sensor would overestimate sunflecks in this particular canopy, based on the measured spectral properties of the leaves. These data are for corn (scans from Welles' 1986 notebook).

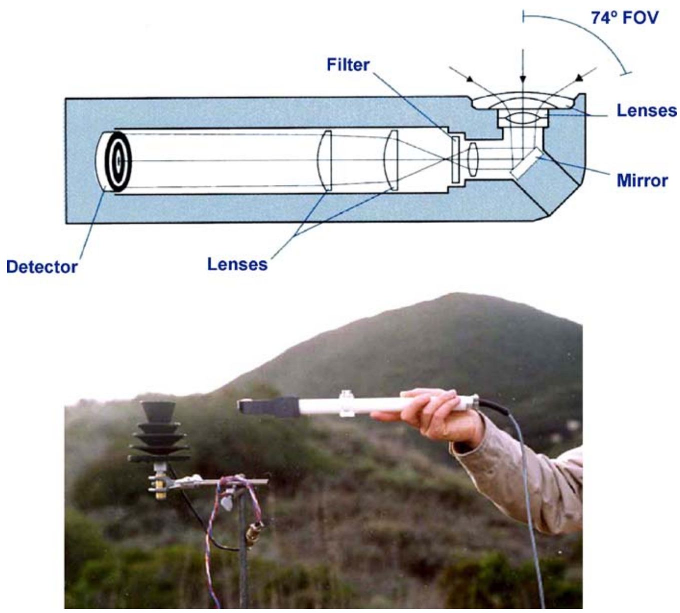


**Fig. 14.** Schematic of the LAI-2000 sensor head, and a prototype of the instrument being tested with the Pine Cone Sensor.

and soil, bright foliage). The latter would be useful for views with significant amounts of sky or (looking down) soil background, but would require a different inversion algorithm. We left it for another day,

## 5. Conclusions

In 1988 John Norman moved back to the University of Wisconsin to replace his retiring mentor, Champ Tanner. There, John has continued to use his creative drive and curiosity to solve measurement problems, and create new tools and ideas. He retired in 2008.

Some of John's devices turned out to be stunning successes, used by scientists all over the world. Other inventions served their purpose, and are all but forgotten. Of far greater importance to John, however, are the students and colleagues he has shared life with during his stays in Pennsylvania, Nebraska, and Wisconsin, and the countless others he has touched around the world. His 40-year career is the true stunning success, and we are all the better for it.

Thank you, John.

## Acknowledgments

Material on John's early career was extracted from an audio reproduction of a talk (available on the AMS website) presented by Bert Tanner at the 28th Conference on Agricultural and Forest Meteorology, introducing the special session honoring Professor John Norman. In his inimitable style, Bert summarized John's professional contributions to the field of Environmental Biophysics, as well as his spiritual contributions to the lives of his friends and collaborators. We thank Bert for this tribute, and are fortunate to have this recording as a reminder of Bert's extraordinary warmth, kindness and sense of humor.

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